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PRELIMINARY DATA ON LUNAR REGOLITH RETURNED BY "LUNA-16" AUTOMATIC PROBE

Academician A. P. Vinogradov

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PRELIMINARY DATA ON LUNAR REGOLITH RETURNED BY "LUNA-16" AUTOMATIC PROBE /8 **

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Text of report presented at the meeting of the Presidium of the Soviet Academy of Sciences on Jan. 21, 1971.

"To ensure during the new five year plan: . . . the performance of studies in space for purposes of. . . continuation of scientific investigation of the moon and the planets of the solar system. . ."

from the recommended resolutions prepared for the 24th Congress of the Soviet Communist Party, dealing with the five-year (1971-1975) plan of development of the national economy of the USSR.

ABSTRACT: Results of a preliminary investigation of lunar regolith returned by Luna-16 automatic probe are reported. They include granulometric data, and description of the optical properties of the regolith, and its petrography and mineralogy, as well as analyses of different parts of the core for major and trace elements. Isotopic composition of the inert gases and some other elements has been determined. The Rb/Sr age of the regolith is 4.85-4.25 billion years.

As reported earlier*, the automatic probe "Luna-16" returned to earth a sample of lunar regolith collected in the northeastern part of the Sea of Plenty at a point (lat. 0.41'S, long. 56°18'E) about 100 km west of Webb crater (Fig. 1).

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*Pravda, October 29, 1970; Priroda, 1970, No. 12, pp. 2-9.
**Numbers in the margin indicate pagination in the foreign text.

Aleksandr Pavlovich Vinogradov is a vice-president of the USSR Academy of Sciences, chairman of the Presidium of the Academy, and director of the V. I. Vernadskiy Institute of Geochemistry and Analytical Chemistry of the Academy. His first papers, published in 1927, dealt with geo- and biogeochemistry of several chemical elements. Vinogradov has worked in general geochemistry, photosynthesis, geochemistry of the crust and mantle, isotope geochemistry, absolute geological dating of the earth, biogeochemistry, as well as sea, nuclear, analytical and space chemistry. Vinogradov directs several scientific Councils of the USSR Academy of Sciences and the State Committee on Science and Technology of the Council of Ministers of the USSR. He is also the editor-in-chief of several scientific journals. He is a Hero of Socialist Labor, a Laureate of the Lenin and State Prizes, as well as a recipient of the Vernadskiy Gold Medal.

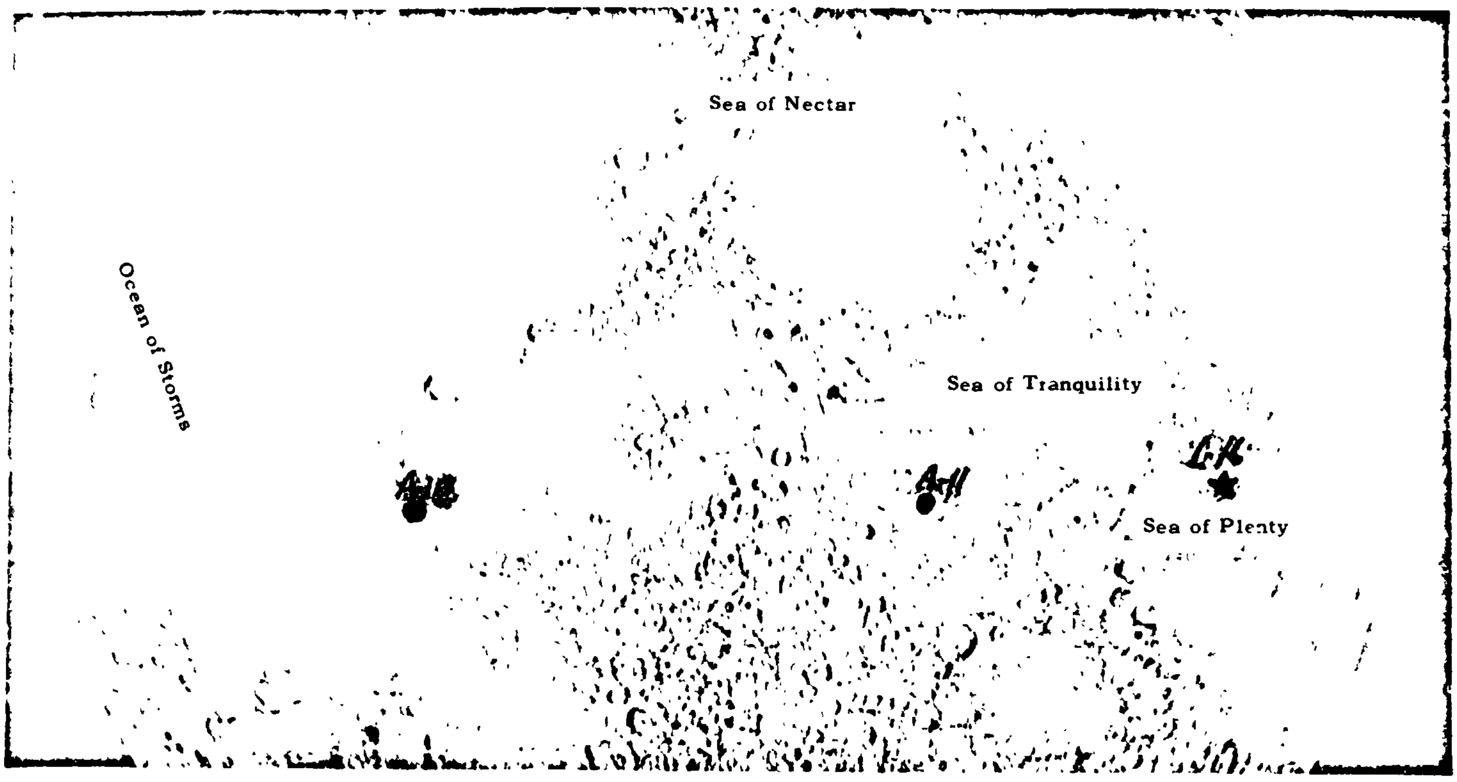

Figure 1. Map of the Moon: Landing Sites of Luna-16, Apollo-11, and Apollo-12.

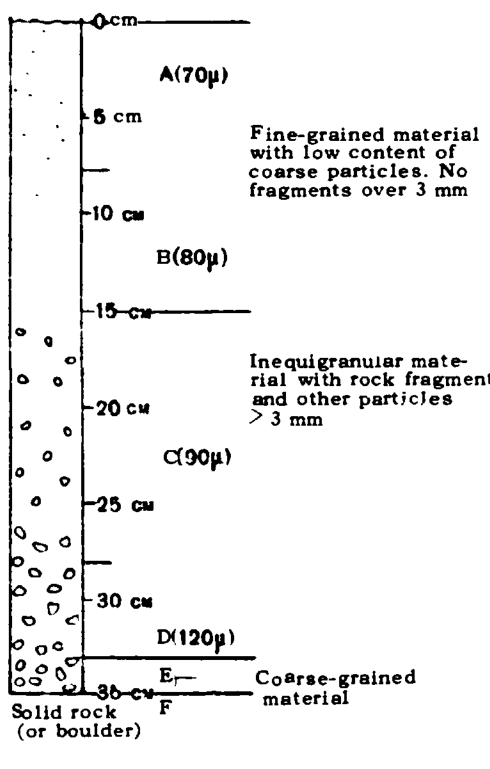

Figure 2. Diagram of Regolith core.

The Sea of Plenty shows signs of quiet subsidence, it is not encircled by mountains and has an irregular shoreline. It is a plain traversed by low (100-300m) branching ridges, containing no large craters with ray systems. The sample of regolith returned by Luna-16 characterizes a new region of lunar plains. We now have samples of the surface rocks from the three large maria lying along the lunar equator on the visible face of the moon; the Sea of Tranquility (Apollo-11), the Ocean of Storms (Apollo-12), and the Sea of Plenty (Luna-16). These samples give us a fairly complete picture of the regolith of lunar plains.

The unconsolidated regolith of the Sea of Plenty was sampled with a coring tube which penetrated it to a depth of 35 cm and was stopped either by solid rock or by large rock framents. The core, which filled the tube completely, was transferred to a core box in a helium-filled chamber. It showed no stratification and appeared to be homogeneous, except for the presence of coarser material at the bottom end. The weight of the core was 101 g. The regolith is dark-gray (nearly black) inequigranular powder, easily molded or adheres into friable lumps. The individual grains are fused, rounded or angular, and their size increases with depth. Grains with diameters ~ 0.1 mm predominate. The distribution of the grains in the core is such as might be expected in repeatedly crushed material. The median size of the grains increases with depth from 70 to 120 μm, and on this basis the core can be divided into several zones: A, B, C, D, and E. Each zone was studied separately. Zones A and B extend to a depth of 15 cm and are composed of fine-grained material with low content of the coarser fraction. Zones C and D (15-33 cm) are inequigranular and contain rock fragments and other particles up to 3 mm in diameter. Zone E is composed of coarse material and extends to the bottom end of the core (33-35 cm) (Fig. 2).

The thickness of regolith at the point of sampling in the Sea of Plenty is only about 35 cm. It is possible, however, that it may be 0.5 - 1 m, or even more than a meter in thickness at other point. Its thickness then is similar to the thickness of regolith in the Ocean of Storms, believed to be 1 - 3 m, and much less than the thickness of regolith in the Sea of Tranquility, assumed to be 6 m. At present, we probably do not know the true average thickness of the lunar regolith.

In its natural state the regolith has a density of ~ 1.17 (1.20) g/cm^3.

By mechanical compaction the density of the regolith can be increased to 2.3 g/cm^3. The heat capacity of the regolith is 0.17 kcal/kg $\cdot$ deg, thermal conductivity, $1.9 \cdot 10^{-3}$ kcal/m $\cdot$ hour $\cdot$ deg, and resistivity, $3.42 \cdot 10^6$ ohm/m. These physical properties of the lunar regolith were determined under a pressure of 10^{-5} for the surrounding medium and a load of 160 kg/m^2 on the sample; they do not correspond to the properties of regolith in its natural state.

Determination of the optical properties of the regolith in the Sea of Plenty showed that its average albedo is 0.069, and 0.105 in the immediate vicinity of the landing of Luna-16. Direct determination of albedo on the sample gave 0.107. Normal albedo is somewhat higher in the red rays: it is 0.086 in the ultraviolet region of the spectrum, 0.126 in the near infrared, and 0.107 in the visible region. The reflectivity diagrams clearly show the presence of a specular component, and the angle of maximum reflection of light is slightly greater than the angle of incidence, increasing with the wavelength of the incident light and with a decrease in the angle of incidence.

Microscopic examination of the lunar regolith shows that it differs greatly from the unconsolidated surface rocks of the earth. Neither does it resemble terrestrial volcanic ash. Two principal kinds of particles can be distinguished in the lunar regolith: particles of primary magmatic lunar surface rocks, similar to basalts, first identified on the gamma-ray spectra of the lunar surface obtained by Luna-10 in 1966 *, and particles which have undergone considerable alteration on the moon's surface. Particles of the first kind are remarkably fresh and angular, such as can be obtained on earth only by crushing samples of unaltered rocks, but the particles of the second kind show unmistakable signs of fusion and agglutination, their surfaces are glassy, and among them there are spherical solidified droplets with vitreous or metallic luster, resembling "cosmic spherules" found on earth. These particles cooled rapidly from melts. The appearance of the regolith particles under the microscope is shown in Fig. 4. The TV image produced by the electron microscope shows how large silicate particles are coated by other small particles (Fig. 3). The content of different particles in the +0.45 mm fraction of the regolith is shown in Table 1.

TABLE 1

Abundances of Different Particles in + 0.45 mm Fractions Separated from Zones A, B, C and D, %

particles	А	Б	В	Г
Gabbro	13.1	17.5	8.1	15.2
Basalt	7.3	9.0	4.9	7.9
Anorthosite	1.1	3.7	2.5	4.5
Breccia	33.9	41.4	35.5	8.3
Scoria and agglutinate	40.0	17.5	41.8	53.6
Glass and mineral grains	2.3	4.0	6.2	6.1
Spherules	1.2	1.3	1.2	1.6
Miscellaneous	1.2	5.7	—	2.6
Total number of particles	838	297	2351	755
Weight of fraction, g	0.230	0.100	0.560	0.260

*Pravda, September 14, 1966. Doklady Akad. Nauk SSSR, 170, No. 3, p. 561 (1966).

There are at least two types of basaltic particles, reflecting the conditions of cooling of balaltic melts: the fine-grained basalts (with glass) (Fig. 5) and the coarse-grained basalts of the gabroid type with ophitic texture. These coarse-grained basaltic fragments account for about 25% of the coarse fraction (>0.45 mm). The principal minerals of these rocks are plagioclase, pyroxenes, ilmenite, and sometimes olivine. The proportion of the minerals in different fragments varies considerably, and it may be stated with assurance that basaltic volcanic activity occurred on the moon, contributing to the formation of the moon's crust, whose thickness is not accurately known at present. In the author's opinion, this universal process of extrusion of easily fused material from the depths of the moon (accompanied by degassing) obeyed the mechanism of zone melting. White feldspathic grains (anorthosite) occur sparingly in the lunar regolith. The origin of lunar anorthosites is not clear, just as the origin of terrestrial anorthosites.

Figure 3. Image of the Fine Fraction of Regolith Particles, formed by Secondary Electrons on a TV Screen of an Electron Microscope. Large Silicate Particles with nearly Hexagonal Cross Section and Growth Lines on the Surface are Partially Coated with very Small Particles.

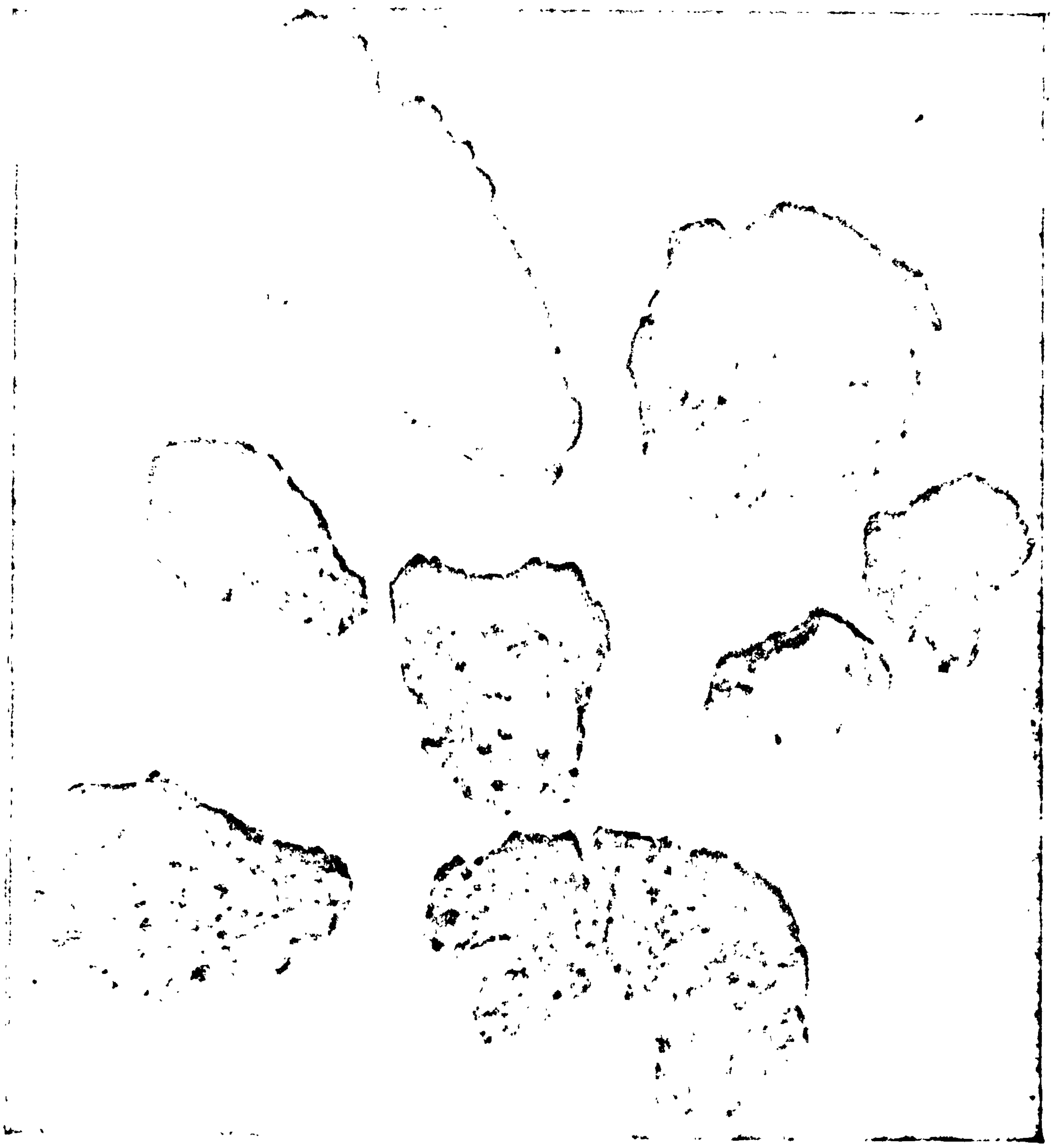

Figure 4. Large Fragments of Lunar Rocks Brought Back by Luna-16.

Upper row: left - fused scoriaceous particle
right - breccia
Middle row: left - two basalt particles, partially porous (the light particle is anorthosite)
right - breccia
Bottom row: left - coarse-grained melanocratic basalt (gabbro)
right - two particles of coarse-grained leucocratic basalt (gabbro)

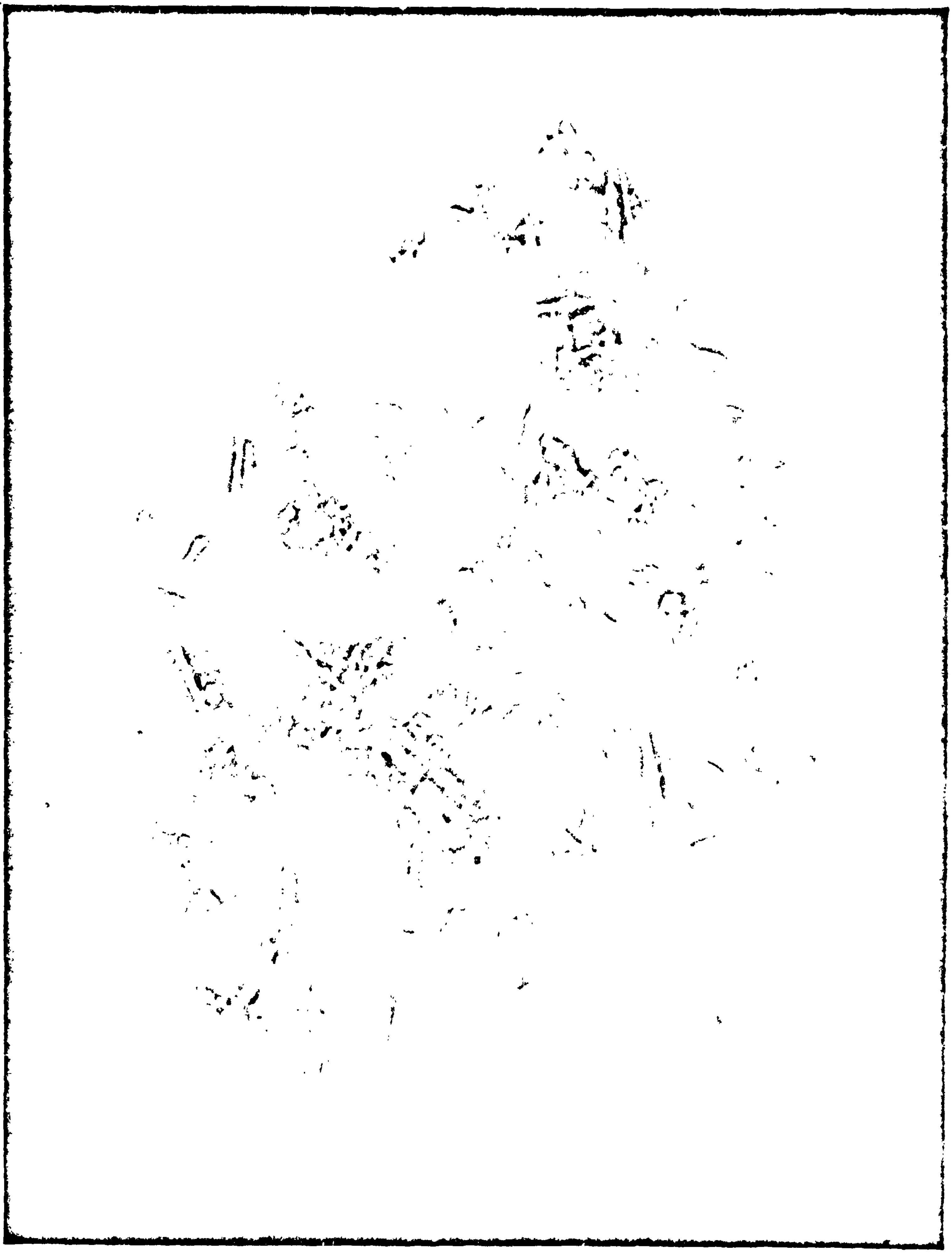

Figure 5. Thin Section of Coarse-Grained Lunar Surface Brought Back by Luna 16 (Micrograph in Polarized Light, Magnified ~ 100X).

The lunar breccias are cemented lithified rocks formed by compaction of finely crushed material of the regolith. They contain all components of lunar regolith in different proportions, i.e., grains of primary magmatic, iron-nickel particles, etc. Some breccias contain rounded fragments, relatively little cement, and are thus easily crushed. Lunar breccias are magnetic and constitute up to 40% of the particles in the regolith.

The scorias and agglutinates are small particles fused together to form aggregates of very complex branching form. They contain all of the regolith components.

At least one half of all the regolith particles show signs of fusion. Some particles are completely glassy, others have been fused on one or more sides. These particles range in color from dark-brown to black, depending on composition (content of Fe, Ti, and other elements). Some particles are vesicular, scoria-like, others have smooth glassy coatings. They are products of typical lunar fusion resulting from instantaneous heating of cold particles.

The quenched drops or spherules vary in form; they may be pear-shaped, dumbbell-like, etc., and in color, some are colorless, others milky, greenish, yellowish-brown, or opaque. Some spherules are hollow. Their luster ranges from vitreous to metallic. They increase in abundance in the finer fractions of regolith. Spherules form at temperatures considerably higher than the melting temperatures of rocks, from the spatter of melt.

Finally, we have the grains of individual minerals which are represented by plagioclase, olivine, anorthite, pyroxenes, spinels, ilmenite, and iron particles. The iron-nickel particles in the regolith will be discussed later. The abundances of different minerals in the regolith sample are shown in Table 2.

TABLE 2

Measurements of Mossbauer Spectra of Lunar Material

Mineral	Fraction of total area of Mossbauer spectrum of iron-bearing minerales,				
	our measurements			Apollo 11 %	
	A3	A3	D8,+0.20-0.45	84-14	45-24
Ilmenite	7.7	6.7	9.2	19.7	26.9
Pyroxene	69.0	71.5	65.1	67.6	60.8
Olivine	18.8	16.7	25.5	4.4	6.1
Iron	4.5	5.1		5.8	2.1
Troilite	$\leqslant 1$	$\leqslant 1$	$\leqslant 1$	$\leqslant 1$	$\leqslant 2$
Magnetite	$\leqslant 2$	$\leqslant 2$	$\leqslant 2$	1.4	2.1

The content of olivine in the Luna-16 sample is fairly high and similar to that in the regolith collected by Apollo-12, and considerably higher than in the samples of Apollo-11. On the other hand, the content of ilmenite in our sample is similar to that in the Apollo-12 samples but much lower than in the Apollo-11 samples.

Olivine occurs in the Luna-16 sample only as irregular fragments of single crystals (in sharply angular particles of different colors) and in the fragments of gabbro. X-ray diffraction studies showed no deformation of olivine structure and no twinning, i.e., the structure had not been strained. The olivine in the lunar regolith is the common α-modification with disordered distribution of magnesium and iron ions. A microprobe analysis of a fragment of olivine gave the following result (wt. %):

$$
\begin{array}{r}
SiO_2 - 36.0 \\
MgO - 27.5 \\
FeO - 33.8 \\
CaO - 0.38 \\
MnO - 0.29 \\
Cr_2O_3 - 0.15 \\
Al_2O_3 - 0.05 \\
TiO_2 \leqslant 0.01 \\
CoO - 0.03 \\
NiO < 0.01 \\
\hline
98.2
\end{array}
$$

The fragment was homogeneous and contained 40 mol.% Fe_2SiO_4. The composition of olivine may be represented as follows:

$$[Mg_{1.14}, Fe_{0.79} (Ca, Mn, Cr)_{0.02}]\ SiO_4.$$

The most abundant minerals in the regolith are anorthite, augite, and ilmenite, in that order. Anorthite occurs as aggregates os small grains in basalts and gabbro, and in spherules in the fine fraction of regolith. No single crystals of anorthite were found.

Other plagioclases were found in triclinic single crystals. Augite-pigeonite occurs in basalt and gabbro fragments, sometimes as the most abundant mineral.

Distribution of the elements in thin sections of basalt was investigated with a microprobe and this helped in the identification of the minerals.

Ilmenite was identified in a gross sample of regolith, where it occasionally occurs in intergrowths with augite. Chromium spinel occurs as dark single crystals. The composition of the magnetic material may be illustrated by a microprobe analysis of sample 3-4b. Analysis of unpolished sample shows irregular distribution of Fe, Ni, Cr, Ti, Si, Al, Mg, and Ca. Areas of concentration of rock-forming minerals and areas of high concentration of Fe and Ni (Fe $\sim$ 6%, Ni $\sim$ 1%) can be distinguished. At some points Fe content reaches 66% and nickel content, 6%. Nickel was not detected in the magnetic particles by Mossbauer spectroscopy, and x-ray analysis of the iron particles showed α - iron (kamacite) but not taenite. The volume of magnetic particles in the regolith sample is less than 1% of the total volume. It is difficult at present to say anything definite about the origin of magnetic particles. As will be seen later, the content of nickel in all samples of lunar regolith (Luna-16, Apollo-11, Apollo-12) is five times higher, on the average, than in basalts, while the content of cobalt is only 1.5 times higher. At the same time, the content of platinoids in the lunar regolith is very low, while in the iron meteorites it is hundreds of times higher than in rocks. Samples of lunar regolith were analyzed by microprobe (for principal elements), mass-spectrometry (for all elements), and by spectrometry and activation analysis (for selected elements).

There is little variation (Table 3) in the composition of the regolith with depth but there is a considerable difference between the composition of regolith and basalts. The composition of Luna-16 sample is similar to the composition of the Apollo-11 and Apollo-12 samples, except for the contents of Ti, Zr, and some minor elements (Table 4).

TABLE 3

Content of Principal Elements in Zones A, B, C and D of Lunar Regolith and in Basalt, wt.%, derived from X-ray Spectral Analyses.

Components	Zone A	Zone B	Zone C	Zone D	Basalt
SiO_2	41.7	41.2	42.5	41.3	43.8
Al_2O_3	15.32	15.40	15.45	15.15	13.65
FeO	16.80	16.55	16.30	16.90	19.35
CaO	12.20	12.80	12.42	12.55	10.40
MgO	8.73	8.82	8.96	8.60	7.05
TiO_2	3.39	3.46	3.30	3.42	4.90
ZrO_2	0.015	—	0.013	—	0.04
Cr_2O_3	0.31	0.25	0.30	0.26	0.28
MnO	0.21	0.20	0.20	0.22	0.20
Na_2O	0.37	0.36	0.36	0.28	0.33
K_2O	0.10	0.12	0.10	0.10	0.15
S	0.19	0.20	0.18	0.25	0.17

Large volumes of F, S, Cl, and other volatiles must have escaped from the moon, but it is possible that the vesicles, observed in some particles of the regolith, contain gases; they are being investigated.

Comparison of chemical composition of regolith and the solid rocks of the three maria shows close similarity and minor variations in the composition of both types of rock. The largest difference in the Luna-16 sample is its low Ti content. It is practically the same as in the samples from the Ocean of Storms (Apollo-12) but is almost two times lower than in the samples from the Sea of Tranquility (Apollo-11). Differences in Mg and Fe contents are small (Table 5).

The crystalline rocks from the Sea of Tranquility have the highest Zr content, and are enriched in Ti, Y, and Sc. The contents of the principal elements and Ni are practically th[illegible]me in the samples from the three maria, and the content of Ni is remarkab[illegible]y similar in their regoliths. Of considerable interest are the compositional difference b[illegible] [illegible]ith and the parent rocks, identical in the three maria. For ex[illegible]mpl[illegible] [illegible]s of Fe, Ti, and Zr are always higher in the parent rocks than in t[illegible] [illegible]d the content of Ni is always higher

TABLE 4

Content of Minor and Trace Elements in Luna-16 Sample (Mass-Spectrometric and Spectrographic Analyses), ppm

Elements	Zone A	Zone B	Zone C	Zone D	Basalt
Li	—	10	—	10	—
Be	—	2.8	2	2.7	—
F	2.65	292	246	277	181
B	4.5	3.9	6	4.6	5
P	—	254	—	200	511
Sc	27	33	23.3	25	20
Cl	66	74	36	72	—
Y	64	73.5	55.3	55	42.5
Co	68	56	44	61	29
Ni	190	137	250	178	147
Cu	36	39.8	35	36	13
Zn	10	20	33	21.5	26
Rb	3	6.3	5.5	—	—
Sr	90	156	—	182	445
Cs	0.06	0.26	—	0.08	0.75
Zr	350	334	354	346	—
Hf	1.1	3.6	1.2	1	0.3
Mo	7	12	3.6	5	1.2
Ga	11	—	4.9	—	1.2
Ge	1.3	11.2	1.2	1.5	2.5
As	0.4	0.36	0.6	0.3	2.9
Se	0.45	0.5	—	0.4	0.7
Br	0.26	0.27	0.24	0.33	1.3
Ru	0.03	0.044	0.01	—	6
Rh	—	0.0037	—	—	—
Pd	0.0086	0.012	—	0.01	0.027
Ag	0.05	0.059	0.02	0.07	0.2
Cd	1	0.75	1	1.3	—
In	0.06	0.025	0.086	0.08	—
Ba	42	259	37	48	206
Sn	1.6	1.4	—	2	4
Sb	0.4	0.3	0.7	0.35	0.5
Te	0.2	—	0.15	0.2	—
W	—	4.7	5.3	7.5	9
Au	0.0033	0.0013	0.003	—	—
Tl	0.3	0.2	—	0.5	—
Pb	6.4	6.6	7	6	7.7
I	0.15	—	0.26	0.14	—
Y	45	49	50	56	58
La	7.3	8	7.4	7.2	7.7
Ce	21	26	24	23	24.6
Pr	4.5	4.7	4.6	4.5	4.8
Nd	20	28	21	23	25
Sm	5.6	6.8	6.2	6.8	7.1
Eu	1.6	1.2	1.3	1.4	1.2
Gd	6.0	4.7	4.6	5.8	4.8
Tb	0.75	1.0	0.9	0.9	0.9
Dy	5.0	5.3	5.0	5.0	5.2
Ho	2.0	2.2	1.9	1.8	2.0
Er	5.0	5.0	5.0	4.7	5.0
Tm	0.4	0.4	0.4	0.4	0.4
Yb	3.5	3.6	3.5	3,5	3.6
Lu	0.28	0.3	0.3	0,3	0.3

TABLE 5

Composition of Regolith and Crystalline Rocks from Three Maria (Principal Elements in %; Trace Elements in ppm)

Oxides, elements	Crystalline rocks			Regolith		
	Sea of Tranquillity Apollo-11	Ocean of Storms Apollo-12	Sea of Plenty, Luna-16	Sea of Tranquility, Apollo-11 (averages)	Ocean of Storms, Apollo-12[2]	Sea of Plenty, Luna-16 (averages)
SiO_2	41	40	43.8	43	42	41.7
Al_2O_3	12	1..2	13.65	13	14	15.33
TiO_2	10	3.7	4.9	7	3.1	3.39
FeO	19	21.3	19.35	16	17	16.64
MgO	8	11.7	7.05	8	12	8.78
CaO	10	10.7	10.4	12	10	12.49
Na_2O	0.5	0.95	0.38	0.54	0.4	0.34
K_2O	0.12	0.065	0.15	0.12	0.18	0.10
MnO	0.4	0.26	0.20	0.23	0.25	0.21
Cr_2O_3	0.6	0.55	0.28	0.37	0.41	0.28
ZrO_2	0.1	0.023	0.04	0.05	0.09	0.013
NiO	(0.007)	—	0.04	0.03	0.025	—
Rb	2.5	0.64	—	2.2	3.2	5.9
Ba	90	72	206	68	420	114
Sr	110	145	445	90	170	169
Yb	2.5	—	3.5	2.5	—	3.5
Y	250	51	54.0	130	130	58.0
Zr	700	170	300	400	670	347
V	45	88	42.5	42	64	61
Sc	110	50	20	55	47	27
Ni	55	54	147	250	200	190
Co	9	40	29	18	42	53
Cu	5	—	13	—	—	37
Li	15	5.5	—	15	11	10
Gd	6	—	11	—	—	4.9

[1] «Science», v. 167, 1970, № 3918, № 3923.

TABLE 6

Th and U Contents, ppm

Elements	Regolith			Crystalline rocks		
	Apollo-11	Apollo-12	Luna-16	Apollo-11	Apollo-12	Luna-16
Th	2.24 ± 0.06	6.0 ± 0.6	0.47 ± 0.05[1]	2.9 ± 0.4	0.88 ± 0.09	1.14 ± 0.1[1]
U	0.59 ± 0.02	1.5 ± 0.2	0.1 ± 0.01	0.7 ± 0.1	0.24 ± 0.035	0.2 ± 0.02[1]
Th/U	3.8	4.0	4.7	4.0	3.7	5.7

* Mass-spectrometric determinations.

in the regolith. The close similarity in Ti content in the parent rocks and in the regolith indicates that the regolith was formed in situ, and was not brought from elsewhere (like volcanic ash). The contents of Ca and Al increase in the regolith. The regolith is enriched in plagioclase and impoverished in pyroxene, olivine, ilmenite, and spinel, in other words it is less mafic than the parent rocks. The minor lithophile elements, Y, RE, Zr, Sc, Th, and U, are enriched in the crystalline rocks of the Sea of Tranquility, as compared with similar rocks of the other two maria (Table 6).

The low content of the platinum group metals and gold in the lunar regolith has been mentioned already, and although there are still very few data on these elements, their abundances in the lunar rocks can be tentatively tabulated (in ppm):

Rock	Pt	Pd	Ir	Ru	Rh	Au
Terrestrial basalts	0.02	0.02	—	—	—	0.004
Crystalline lunar rocks						
Apollo-11 samples	—	0.006[1]	0.0001--0.01	—	—	—
Same	—	0.1[2]	—	—	—	0.0016[4]
Apollo-12 samples	—	—	0.0013[3]	—	—	0.0011[3]
Luna-16 samples	—	0.027	—	6.3	—	—
Luna-16 sample						
Regolith						
Apollo-11 samples	—	0.04[3]	-	—	—	0.0021[4]
Luna-16 sample	—	0.01	—	0.027	0.0037	0.002
Iron meteorites	12.0	3.7	2.8	—	—	1.0

1 Baedecker, and Wasson, Science, v.167, No.3918, 1970.

2 Morrison et al, Science, v.167, No.3918, 1970.

3 Laul, Keays, Ganapathy and Anders, Earth and planetary Science Letters, v.9, No.2, 1970.

4. Wanke et al, Science, v.167, No.3918, 1970.

Determinations of the rare earths have not been completed. The isotope ratios in the regolith: $Li^7/Li^6 = 12.28$, $K^{39}/K^{41} = 14.00 \pm 0.18$, and $Rb^{85}/Rb^{87} = 2.57 \pm 0.04$ (in an average sample), correspond to these ratios on earth. It should be noted that the lithium isotope ratio in meteorites is different from that in the terrestrial rocks.

It is known that solar wind causes spallation. Spallation products, Na^{22}, Al^{26}, and others have been found in the lunar regolith, and Al^{26}, for example, gives 173± 113 dpm/kg. Investigation of spallation products is continuing and it is intended to obtain data for zone A and for the deepest zone E of the core. These data should be very informative.

The infrared spectrum of the regolith has a broad structureless absorption band in the region of silicon-oxygen bond vibrations. Heating of a sample of regolith in argon atmosphere to 1000°C resulted in appearance of well-defined structure in this region of the IR spectrum, of absorption bands produced by independent SiO_4 groups and by various silicate structures, tectosilicates, etc. It may be supposed that heating of the sample removed the effects of irradiation of regolith.

The effect of solar wind, that is, metamictization of minerals and formation of spallation products, extends to only a shallow depth in the rock (3-5 cm). Measurements of induced activity in the upper and lower zones of the regolith are projected, and their results may throw light on the history of accumulation of the regolith.

The sample of regolith contained unusual assemblages of the inert gases, whose content was independent of the depth in the core. The abundances and isotopic composition of the inert gases in zone D of the core are shown in Table 7.

TABLE 7

Content and Isotopic Composition of Inert Gases in Dust Particles $10^{-8}cm^3$

Isotopes and Rocks	Sea of Plenty, sp. G7-1 d	Apollo-11		
		Schaffer and Zahringer	Reynolds	Hindenberger
^4He	18 000 000	(11—19) 000 000	29 000 000	9 000 000
$^4He/^3He$	2670	2540	2130	2770
^{20}Ne	340 000	313 000	530 000	125 000
$^{20}Ne/^{22}Ne$	12.80	12.4	12.85	12.6
$^{21}Ne/^{22}Ne$	0.0332	0.0340	0.0332	0.0352
^{40}Ar	53 000	38 500	57 000	56 000
$^{40}Ar/^{36}Ar$	0.98	1.1	1.126	3.04
$^{36}Ar/^{38}Ar$	5.26	5.20	5.19	5.08
^{84}Kr	22	21	37	8.5
^{132}Xe	8.5	10	4.6	2.2

The predominant components of the inert gases are the gases of the solar wind. Their composition differs sharply from the composition of the terrestrial and meteoritic gases, and their concentration is very high, higher by several orders of magnitude than on earth or in meteorites. The contents of He and Ne, however, are similar to those in some meteorites enriched in the inert gases. The argon isotopic composition is unusual, the Ar^{40}/Ar^{36} ratio is near unity, but the $Ar^{36}/Ar^{38} \sim 5.25$ ratio is the same as on earth. The amount of Ar^{40} is 4-5 times greater than can be formed in rocks by decay of K^{40}. The xenon isotopic composition also differs from that on earth and is being investigated further. The Sea of Plenty regolith is nearer in the content of inert gases to the regolith of the Sea of Tranquility than to the regolith of the Ocean of Storms. The first determinations of the age of the moon by the Rb/Sr method on the regolith fines gave $4.85 \cdot 10^9$ and 4.25 ± 10^9 years. The average ages by the isochron method are $4.45 \cdot 10^9$ and 4.65 ± 10^9 years. The same ages were obtained from the Pb^{206}/Pb^{207} ratio. The samples from three maria give practically the same age for the moon, corresponding to the age of the earth. It is difficult to date the moon by the K/Ar method. The exposure age of the regolith is of particular interest.

It may be concluded that the lunar rocks from the three maria are of the same composition, all are basalts differing very slightly in composition. These compositional variations may be ascribed to the different conditions of formation of parent magmas (by zone melting). The compositional differences among the regolith samples from the three maria also are slight and may be explained by somewhat different postdepositional history of the rocks.

The rocks of the Sea of Plenty are chemically nearer to the rocks of the Ocean of Storms, but the content of the inert gases in the regolith of the Sea of Plenty is nearer to that in the regolith of the Sea of Tranquility.

Let us pass now to some preliminary conclusions. It is premature to make any definite statements concerning the character of the processes on the lunar surface. We shall use the results of investigation of the Luna-16 sample and compare them to the published data on the Apollo-11 and Apollo-12 samples. The rocks from the Sea of Plenty, Sea of Tranquility, and the Ocean of Storms are remarkably alike petrologically, mineralogically, and chemically, but there are minor compositional variations. The vast maria, lying along the lunar equator, are depressions flooded with mafic lavas. Long ago, during the time of intensive volcanism on the moon, great volumes of basaltic magma were extruded and its volatile components were dissipated. The variations in the contents of Fe, Ti, Zr, Ba, and other elements in lunar basalts may be explained by the conditions of extrusion, depth of magma chambers, temperature, and some other factors, for example, the content of iron in the parent magma. It is possible that anorthosites, rhyolites, and other differentiates of basaltic magma occur on the moon. The thickness of the basaltic crust of the moon is not known.

The age of the surface lunar rocks, i.e., the age of the moon, is the same as the age of the earth. Lunar "seas" are covered with regolith of variable thickness, at the point of sampling in the Sea of Plenty it is no more than 0.5 m thick. The range of variation in the thickness of the regolith probably amounts to a few meters. The regolith is a mixture of lithic fragments, and mineral grains of different size, color, and shape. Some grains are rounded by fusion, others are angular. The proportion of different grains varies with depth, but no stratification was observed in the Luna-16 core. The regolith was formed by crushing of rocks at high temperature, as indicated by the presence of fused grains and glassy spherules. The lunar regolith does not resemble terrestrial volcanic sand. Its composition is slightly different from the composition of solid lunar rocks, it is poorer in mafic components, and must have lower melting temperature than the primary basalts. Before discussing the origin of lunar regolith let us consider the principal factors of lunar "weathering". One of these is the temperature change from lunar day to lunar night, amounting to $\sim \pm 100°C$, to which the lunar surface has been subjected for billions of years. Another factor is irradiation of the lunar surface by solar wind and galactic cosmic rays. The near vacuum environment of the lunar rocks and meteoritic impacts must also be considered. The sharp temperature changes must affect the strength of the lunar rocks but the importance of this factor cannot be estimated at present. The effect of solar wind and galactic radiation is much greater. Our observations show that the regolith has been affected by solar wind to a depth of 35 cm, for a sample from zone E had a very high content of the neutral solar gases, and the infrared absorption spectrum of core revealed signs of irradiation. We must await the results of determination of the spallation products in the deeper zones of the regolith before deciding whether its material undergoes mixing in situ, or whether the history of its formation is recorded in it layer by layer.

Penetration of radiation is not deep, a few centimeters of rock. Investigation of metamict minerals, containing radioactive elements, shows that they are weakened, their structure is deformed, etc., but metamictization does not destroy them completely. The sample of lunar regolith is being investigated now for signs of metamictization. Lunar surface rocks are irradiated after crushing, solar wind does not participate directly in formation of regolith (its fusion) but does affect the strength of starting material. It is usual to ascribe the formation of maria, and of their regolith, to meteoritic impacts. It is interesting to try and visualize the fall of meteorite swarms on the visible face of the moon, on the maria located along the lunar equator. It is difficult to explain why meteorite swarms should have fallen only on the visible face of the moon, on that part of it which is most convex in the earth's direction. The most reliable proof of the "work" of meteorites would be discovery of meteorites on the moon's surface, but meteorites and micrometeorites impact on the moon with cosmic velocities, and experiments and calculations show that one gram of meteoritic matter impacting on the moon is capable of exploding, crushing from one hundred to a thousand times as much of lunar rocks. During this process rock fragments leave the surface of the moon at great velocities, and a part of them may leave the gravitational field of the moon and fall on earth (as, for example, eucrites). This possibility must be borne in mind in considering the origin of lunar regolith. It may be assumed that a certain portion of meteoritic matter, very small perhaps, will remain on the moon's surface. Preliminary data on the presence of meteoritic matter in the lunar regolith were given above. There is no doubt of its presence, but this fact in itself is not sufficient to explain the formation of all of the lunar regolith by meteoritic impact.

One more point should be brought out. The most characteristic feature of lunar volcanism is extrusion of basaltic lavas into high cosmic vacuum. Lunar magmas rise to the surface and burst through the roof rocks with explosive force. Liquid magma must spatter on reaching the vacuum and its volatile components must escape with very high velocities. It would be highly desirable to devise an experimental model of this process, the results should be quite valuable for solving the problem of origin of the lunar regolith, and also throw light on the geochemical processes on the earth during the first billion years of its evolution.

Despite its relative shortness, the study of material brought back by Luna-16 has very clearly indicated three geochemical problems which hopefully can be solved. These are: a) origin of the regolith, b) the fraction of meteorite material in the regolith, and c) the basalt melting mechanism and composition.

Even though we now only have a vast amount of unreduced factual data on the lunar surface material from only a few sites, we think that it will be possible to derive some general relationships in the next few years and thus solve the principal problems of lunar evolution.

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